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Performance Trades for Long-Haul Communication in Deep Space

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ABSTRACT

A study was undertaken as part of the NASA BEACON architecture project, in order to find the most cost-effective methods for satisfying the anticipated increases in NASA's demand for long-haul communications from deep space to Earth. We considered a variety of architectural styles in our search: radio communication at X-, Ka-, or W-band; optical communication; single hop communication systems with a large Earth-based aperture; single hop with large space-based aperture in the general vicinity of the Earth; and multihop communication with a number of space-based relay terminals between the Earth and the target. For Earth-based radio systems, we also considered monolithic apertures, and arrays of antennas such as those described elsewhere in this conference.

We assumed that each of the architectural styles could be scaled to higher capacity by replication. For the single-hop approaches, we assumed that the system capacity would grow proportional to investment; for the multihop approaches we assumed that the capacity would grow with the square of investment as expected based on the inverse square law for space loss.

Considering only bit rate and implementation cost, and within prevailing conditions of ground and spacecraft costs, we found that single hop large Earth aperture systems based on either optical telescopes, or on arrays of medium-sized (around 10m) Ka-band antennas, offer a five-to-tenfold advantage over the alternate solutions considered. This conclusion applies to the range of data rates from 100 kbps to 1 Gbps at typical Mars distances (2.3 AU) with typical spacecraft characteristics. At data rates approximately greater than 1-100 Gbps at Mars distances, space-based multihop solutions become competitive with the Earth-based approaches.

Keywords: deep space, radio, optical, communication, single hop, multihop, relay, array, Mars, architecture

INTRODUCTION

The NASA Space Science Enterprise, and the NASA Human Exploration and Development of Space Enterprise, each anticipate a significant increase over the next two decades in demand for long-haul communications services from deep space to the Earth. The range of distances to be considered is on the order of 0.1 AU up to >200 AU, while bit rates needs are expected to be at least >10 Mbps and perhaps >100 Mbps under routine operating conditions for mid-range distances of a few AU. For the near term, the demand is driven by increasing data production from more capable instruments onboard the spacecraft, by an increasing number of missions at distances beyond Earth orbit. In the long term, demand is driven by missions with extreme communications challenges such as great distance, subsurface environments, or support for human exploration. Emergency and critical operations also create an increasing demand for high reliability communication from spacecraft with potentially limited resources or in highly non-ideal operating environments.

A study was undertaken as part of the NASA BEACON architecture project, in order to find the most cost-effective methods for satisfying the anticipated demand. This paper serves to report preliminary conclusions from the study, which were obtained using simplified conditions sufficient to narrow down the field of competing options. Additional work will be required to obtain realistic treatments for actual selection among alternatives.

OPTIONS CONSIDERED

We considered several alternative architectural styles for meeting the increase in demand, using either radio frequency (RF) communication or optical communication in the 1 micron wavelength band. Both single hop and multihop systems were considered. The single hop systems considered were those with large Earth-based aperture, and those with a large space-based aperture in the general vicinity of the Earth. We considered X-band (8.4 GHz), Ka-band (32-34 GHz), and W- or V-band (around 60 GHz) for the RF space apertures. Only Ka-band was considered for the RF earth apertures. The options for RF ground apertures were further refined by considering various types of ground antennas: 34-meter Beam-Waveguide antennas, 70-meter antennas or their equivalents, and arrays of medium sized antennas around 10 meters in diameter. The multihop systems considered had various numbers of space-based relay terminals between the Earth and the target.

EVALUATION OF OPTIONS

We compared the architectural styles on the basis of downlink bit rate and cost. Any of these architectural styles could be applied to meet the anticipated demand, so some criterion is needed to select among the options. Within our evaluation, we considered the most desirable style to be the one with the highest ratio of bit rate to cost. If it were to happen that the most desirable style itself did not inherently contain enough bit rate capacity, we assumed that any of the styles could be scaled to higher capacity by replication. For the single hop systems, we assumed that the system capacity grows linearly with investment. For the multihop style, we assumed that system capacity grows with the square of investment as a consequence of inverse square law for space loss; to first order, if the number of relay terminals in a multihop system is doubled, the distance between terminals is halved and the data rate can be quadrupled. We neglected any potential economies or diseconomies of scale in any of the replication, and potential inefficiencies (typically a factor of two) in the deployment of multihop relay terminals resulting from constraints of orbital mechanics.

Our consideration of cost was limited to only the implementation cost of the ground terminals, and the space-based terminals if any. We did not include the operating cost of the systems after installation, nor the cost of the customer spacecraft communications equipment. In most cases the full implementation cost of new terminals on the Earth or in space was used. However, in two cases, the marginal cost for "piggyback" installations was used. One case was the possible addition of Ka-band capability to the existing 34m Beam-Waveguide antennas of the Deep Space Network (DSN). The other case was possible addition of a deep-space RF communication capability to a hypothetical spacecraft stationed in space near to the earth for some other reason. One possible location for such a spacecraft is the Earth-Sun Lagrange point designated "L2", so we labeled this general class of spacecraft as "L2 data relay satellites" (L2DRS). For the purposes of our comparison the exact location is not important,; it is only important that the spacecraft be in the general vicinity of the Earth (say, within 0.2 AU) and have few visibility restrictions due to Earth or Moon proximity.

Our consideration of bit rate was based on physical limits. We did not investigate the effects of the customer data source distribution (e.g. Mars vs. multiple targets spread among the outer planets) or limitations such as computation speed, data storage, or spectrum allocations. System redundancy for reliability was not included, which may be a significant penalty for the space-based systems; in this respect we are putting the space-based systems on the best footing possible for comparison to the Earth-based systems. Any potential challenges with scaling of optical systems, such as the difficulty of coherent arrays or the construction of significantly larger telescopes, were also neglected. In this respect we put optical systems on the best footing possible. We included realistic allowances for Earth-based weather effects.

Sample link characteristics for RF and optical communication appear in Tables 1 and 2 respectively. These are applied to the various architectural styles as listed in Table 3, using the presently available ranges of cost for each style.

Table 2. Sample Optical Link Characteristics

	Mars to 10m Earth	Mars to 7m Earth-Sun L2
Data Rate (Mbps)	52	52
Link Margin (dB)	3	3
Wavelength	1064 nm	1064 nm
Range (AU)	2.3	2.3
Atmospheric Transmission at Zenith (%)	80	100
Zenith Angle (degrees)	70	0
Aperture Diameter at S/C (m)	0.4	0.4
Laser Efficiency (%)	25	25
Laser Output Power (W)	43.5	43.5
Total DC Input Power (W)	200	200
Detector Quantum Efficiency	70	70
Adaptive Optics ?	yes	n/a
Assumed Era of Technology	2020	2020

Table 1. Sample RF Link Characteristics

Link Parameter	Unit	Design Value	Notes		
Range	AU	2.3			
Frequency	GHz	32			
TRANSMITTER PARAMETERS					
Total Transmitter Power	dBm	50.01	0.1		kW
Transmitter Waveguide Loss	dB	-2.00	XMTR Circuit Losses		
S/C Antenna Gain	dB	56.24		2.5	0.6 Diam, eff
Antenna Pointing Loss	dB	-0.50			
EIRP	dBm	103.74			
PATH PARAMETERS					
Space Loss	dB	-293.28			
Atmospheric Attenuation	dB	-1.20	Canberra 90% weather		20 deg elev
RECEIVER PARAMETERS					
Earth Station Antenna Gain	dB	84.40		70	meter 20 deg elev
Receiver Circuit Loss	dB	0.00		0	
Pointing Loss	dB	0.00			
Polarization Loss	dB	-0.20			
TOTAL POWER SUMMARY					
Total Received Power	dBm	-106.54			
Noise Spectral Density	dBm/Hz	-180.15		70	Nominal
Pt/No	dB-Hz	73.61			
CARRIER PERFORMANCE					
Received Pt/No	dB-Hz	73.61			
Telemetry Suppression	dB	-54.91		1.569	rad TLM mod index
Range Suppression	dB	-0.20			
Carrier Loop Noise Bandwidth	dB	0.00		1	Hz BL
Carrier Loop SNR	dB	18.49			
Recommended Detection SNR	dB	13.00			
Carrier Loop Margin	dB	5.49			
DATA CHANNEL PERF.					
Received Pt/No	dB-Hz	73.61			
Telemetry Data Suppression	dB	0.00			
Range Suppression	dB	-0.20			
Pd/No	dB-Hz	73.41			
Data Rate	dB-Hz	-69.91		9.80E+06	bps
Available Eb/No	dB	3.49			
Radio Loss	dB	-0.20			
Subcarrier Demod Loss	dB	-0.20			
Symbol Sync Loss	dB	-0.20			
Waveform Distortion	dB	0.00			
Output Eb/No	dB	2.89			
Required Eb/No	dB	-0.10	CCSCS Rate 1/6 Turbo BER=10**-6		
Performance Margin	dB	2.99			

Table 3. Comparison of Architectural Styles

Architectural Style	Bit Rate Capacity (Mars near maximum range, reference spacecraft characteristics)	Cost for Single Reception Site	Capacity Scaling with Investment	Notes
10 m Photon Bucket Earth Station	50 Mbps	35-40 $M	linear	1, 3,4.
7 m Photon Bucket L2 Data Relay Satellite	50 Mbps	500-750 $M	quadratic	2, 3.
1m optical relay satellites	1 Mbps	100-500 $M	quadratic	3.
Prototype Array Ka-band	10 Mbps	10-20 $M per 70-meter equivalent	linear	4.
100x70m equivalent Array Ka-band	1000 Mbps	1000 $M	linear	4.
70m Ka-band new	10 Mbps	100 $M	linear	4.
34m Ka-band new	2 Mbps	40 $M	linear	4.
34m Ka-band upgrade	2 Mbps	2-3 $M	---	5.
4.5m Ka-band L2 Piggyback Relay	0.023 Mbps	30-50 $M	---	
15m Ka-band L2 Piggyback Relay	0.26 Mbps	30-50 $M	---	
15m 60 GHz L2 Piggyback Relay	0.9 Mbps	30-50 $M	---	

Notes:

1. All sky coverage possible with a single station, but duty cycle limited by Earth horizon. Must have three sites for continuous contact to user, but can have three simultaneous contacts to users in different parts of the sky once three sites are installed.
2. Nearly all-sky coverage possible with a single satellite. Continuous contact possible with a single satellite from a single user.
3. Includes launch cost.
4. Requires three sites on Earth for continuous coverage. Reference point for capacity scaling depends on whether capacity is spread over sky (scaling starts from completion of the third station) or for a single direction in the sky (scaling starts from the first station).
5. There are a limited number of existing stations for which this option is valid.

Figure 1 summarizes the comparisons between the various architectural styles using the data from Table 3. The ellipses indicate the range of downlink bit rate and implementation cost associated with each style, and the colored lines indicate the direction of scaling for higher capacity systems where applicable. For convenience, a scaled data rate is also indicated for missions at an extreme range, corresponding roughly to the Kuiper belt (230 AU).

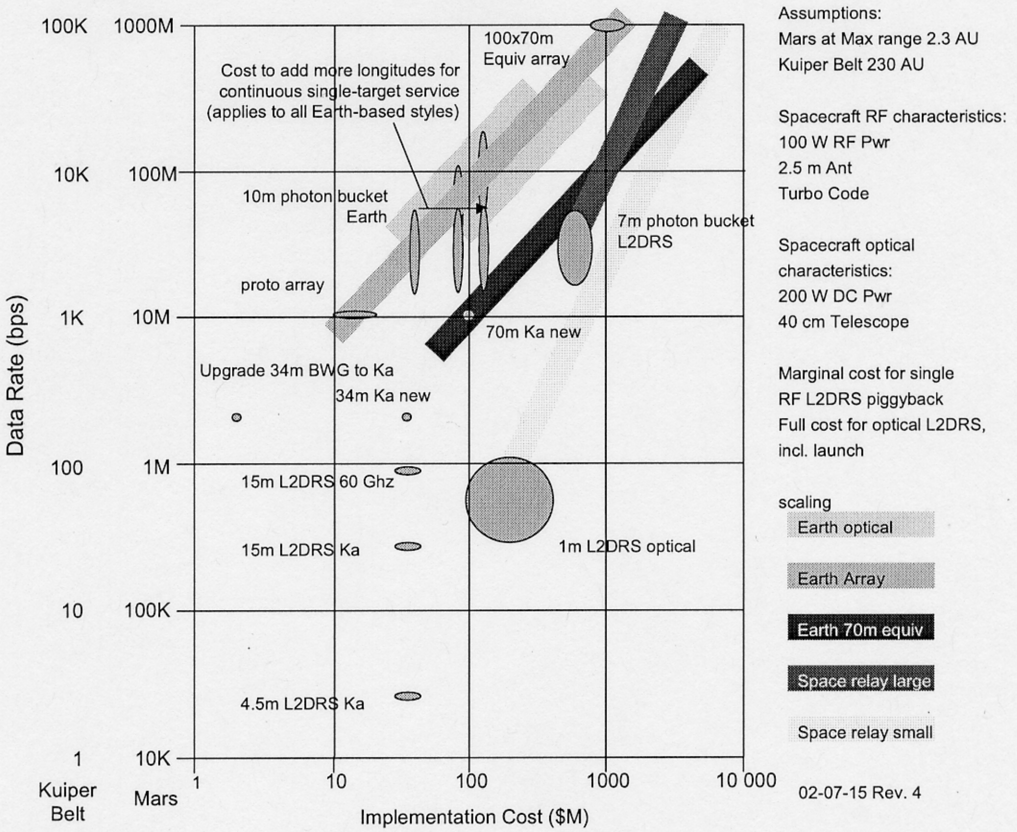

Figure 1. Comparison of Architectural Styles

CONCLUSIONS

Single hop large Earth aperture systems offer a five-to-tenfold advantage in downlink bit rate per unit cost compared to the alternate solutions considered. Either optical telescopes, or arrays of medium-sized (around 10m) Ka-band antennas are very good and appear to offer about the same downlink bit rate per unit implementation cost. Since this paper made a number of simplifying assumptions, the comparison between optical and RF earth stations is too close to definitively identify one or the other as superior. Either optical or RF could prevail when other factors are considered.

This conclusion is applicable only under a certain range of conditions, primarily governed by a limitation that the anticipated data rates fall in the range from 100 kbps to 1 Gbps at a typical Mars distance (2.3 AU), and to a lesser degree governed by typical spacecraft characteristics. Scaling to other distances is valid, although substantial variation of the spacecraft from the assumed characteristics could alter the range over which Earth-based solutions are preferable.

Space–based multihop solutions are competitive with the Earth-based approaches for data rate demands significantly higher than presently anticipated for NASA's needs. The demanded data rates would have to rise to approximately greater than 1-100 Gbps at Mars distances for multihop to be an attractive solution, or to correspondingly high data rates from other distances. Alternatively, spacecraft costs would have to fall by 5x – 10x for multihop to be competitive at the anticipated data rate needs.

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